A New Begin

New theories suggest the universe began with a Big Burp and not a Big Bang. But astronomers are still looking in the dark. By Mark Sincell

THE UNIVERSE WE KNOW is a big old lumpy mess filled with all manner of particles, light waves, and who knows what other exotic stuff. But it wasn't always that way. Somewhere in the neighborhood of 14 billion years ago, when the universe was only a few microseconds old, cosmologists believe that it was a superheated soup of subatomic particles called quarks, the building blocks of protons, smooth enough to make a French chef weep with jealousy.

Understanding how that primordial soup grew into the present vast foamy mixture of dense galactic clusters and empty space has occupied Mike Turner for most of his distinguished career. And for the moment, Turner, a cosmologist at Fermilab in Batavia, Illinois, and many of his colleagues think they have a pretty good idea how it all works. It's a little theory they call the Standard Hot Big Bang.

In the beginning, there was nothing. Then, with a big bang, an almost infinitely small, hot, and dense universe exploded into existence. Mere seconds later, the soupy universe had cooled enough for quarks to combine into positively charged protons and their neutral cousins, neutrons—and then for neutrons and protons to fuse into the nuclei of light elements like hydrogen, helium, and lithium. A few hundred thousand years of cooling later, these nuclei combined with negatively charged electrons to form atoms. Finally, gravity pulled the atoms together to form stars and galaxies. "The theory is so successful that grander theories will have to swallow the Hot Big Bang whole," says Turner. "It will be enlarged, not overturned." And that is likely to happen sooner rather than later.

In the past year, a rash of new discoveries has prompted cosmologists to start rethinking the Big Bang. Naturally, this makes them very happy. "The year 2000 was the most exciting

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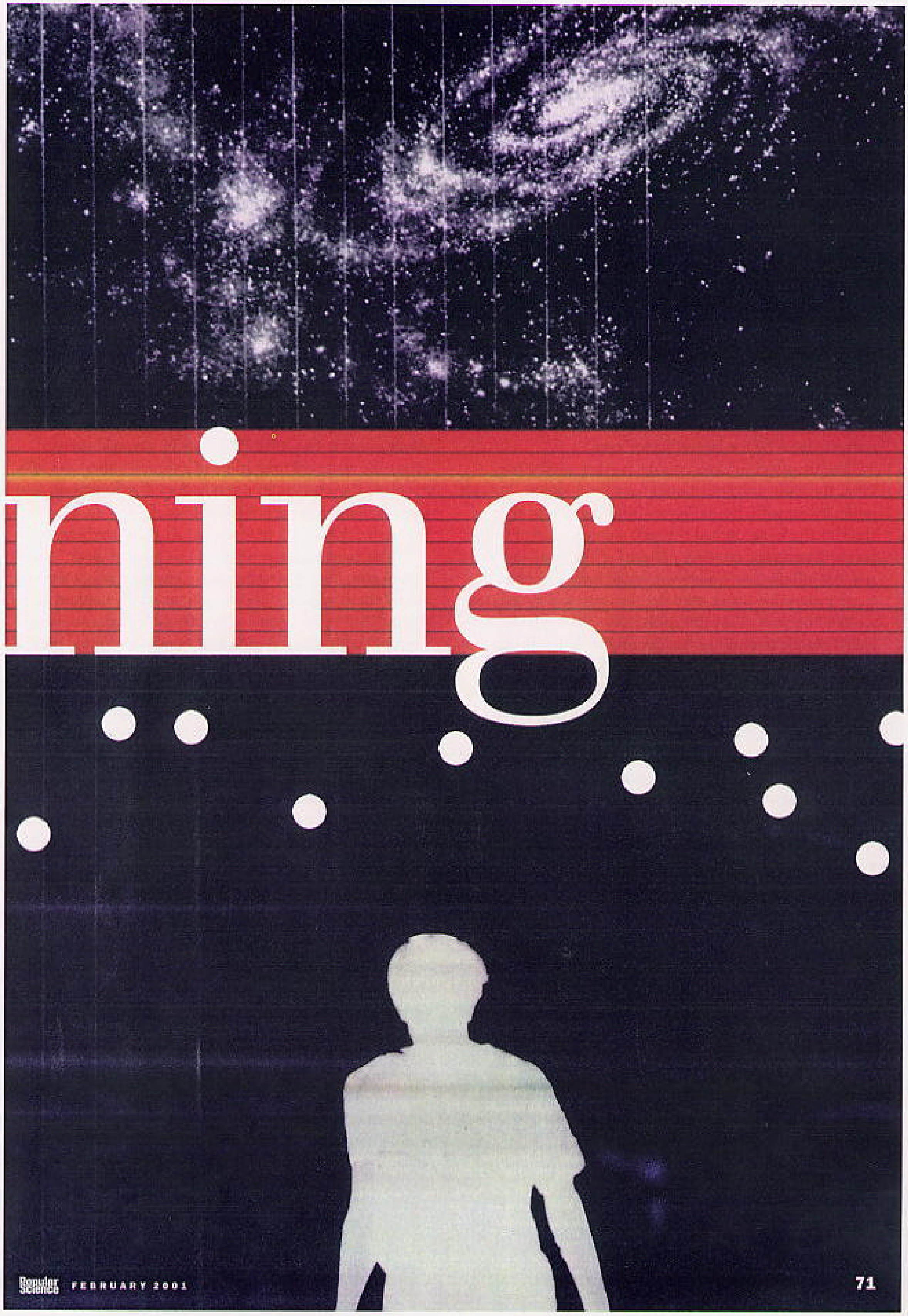
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for cosmology since the 1930s," says Max Tegmark, a Princeton physicist. A diverse array of experiments carried out in space, on mountaintops, and suspended from balloons is now giving cosmologists their most accurate accounting ever of the makeup of the universe. And what they are finding is nothing like what they expected to see. Scott Dodelson, a physicist at Fermilab, sums it up nicely. "All the evidence points in one direction, but it is a bizarre direction."

The direction is called inflation. In the early 1980s, a theory began to circulate that claimed that the entire visible universe is actually the progeny of one of many tiny little gas-bubble universes that each expanded rapidly during the first 10^{-32} seconds after the Big Bang. Call it the Big Burp. Although the theory doesn't say exactly how much the universe grew during this inflationary period, says Turner, "We think that in that growth spurt, the universe grew by the largest factor ever."

The theory of inflation makes two key predictions. First, the early universe should have been almost, but not perfectly, smooth. Sound waves from the fading echo of the Hot Big Bang rippled through a dense fluid of radiation and particles, creating patterns of high and low density. An inflationary expansion would have stretched out these primordial waves until the universe was as serene as a reflecting pool on a calm spring day. Although the so-called cosmic microwave background radiation broke free from the fluid when the universe reached the ripe old age of 300,000 years, it should still carry the fossil imprint of the echo of the Big Bang. Sure enough, in 1992 NASA's Cosmic Background Explorer satellite found a striking confirmation of inflation's first prediction: a one-thousandth of a percent variation in the brightness of the cosmic background radiation.

The second prediction was more troubling. Inflation demands that the universe be "flat," but not in the conventional sense of a tabletop. In the four-dimensional world inhabited by cosmologists, "flat" means that parallel lines never converge. In a "curved" universe they would eventually cross like two lines drawn on the surface of a balloon. For the universe to remain flat, however, the total density of matter and energy must be exactly equal to a certain critical value. But every attempt to weigh the universe came to the same conclusion: Its density was at most 40 percent of the critical density.

That is where things stood when in 1993 two independent teams—Saul Perlmutter and his team at the Lawrence Berkeley Lab in California, and Brian Schmidt's team at the Harvard University Center for Astrophysics—started weighing the universe. To put the entire universe on a scale, both teams searched digital images of large swatches of sky for the sudden appearance of exploding sun-like stars called Type 1a supernovae. These garden-variety supernovae have a special property. Within a week of exploding, and before fading into obscurity months later, all Type 1a supernovae reach the same peak luminosity—about equal to the 100 billion stars in a typical galaxy. Since the observed brightness of a distant supernova falls in strict proportion to its distance from Earth, astronomers can calculate the exact distance to each Type 1a. Provided they can catch it before it reaches its peak brightness.

"Type 1a supernovae are a real pain in the neck," says Perlmutter, "because each galaxy only produces about two of them every thousand years, and they happen randomly." But by sweeping up 10,000 galaxy images every few days with a digital wide-field camera mounted on a robotic telescope, Perlmutter's team is guaranteed to find a few newborn supernovae. Follow-up pictures from a worldwide array of telescopes reveal the color of the fading supernova flash, which Perlmutter's team uses to deduce how much the universe has expanded in the time it took the light to travel to Earth. And when he compared the supernova distances with the amount of universal expansion for more than 40 supernovae he had gathered by the end of 1999, Perlmutter got the surprise of his life. "The expansion of the universe is speeding up," he says.

That is not supposed to happen. Ever since the universe expanded into existence, firing particles and radiation into the void like balls from a cosmic cannon, the attractive

COSMOS COMBING

AN ARRAY of innovative experiments is helping fuel a recent explosion of advances in cosmology. With the Supernova Cosmology Project, for instance, astronomers are learning how fast the universe was expanding at different times in its history. This and other projects are exploring the age and geometry of the universe, the nature and amount of dark matter and energy, the manner in which

DESPERATELY SEEKING SUPERNOVAE

How fast is the universe expanding? The Supernova Cosmology Project at Lawrence Berkeley Lab uses several observatories (red dots) to find supernovae that act like yardsticks. After a new moon, they observe 1,000 galaxies at a time, looking for the elusive Type 1a supernovae.

supposed to happen.


Saul Perlmutter got the surprise of his life when his team started weighing the universe.

gravitational force of all that light and matter has been trying to pull the universe back together. The net effect should be to slow the expansion. Instead, Perlmutter's team found the opposite. "It's as if we weighed the universe," he says, "and found out it was negative."

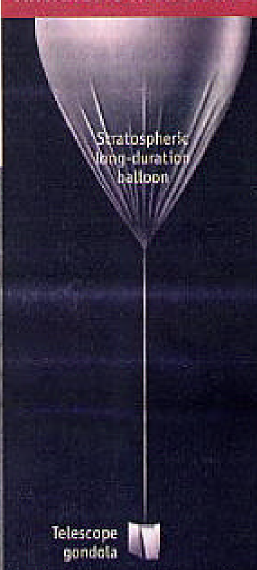
The total weight of the universe is less than zero? Not exactly. Although the attractive force of gravity is proportional to the total mass of an object, Einstein's theory of gravity also contains a quantity—called the cosmological constant, or "dark energy"—that pushes back. Adding dark energy increases the weight of the universe, and it counteracts the pull of normal matter and accelerates the cosmic expansion like air blown into a balloon.

The surprises weren't over yet. Since matter is attractive and dark energy is repulsive, the rate of cosmic acceleration is proportional to the difference between the density of the universe's mass and the density of the dark energy. Using the best current estimates of the mass density, Perlmutter's team calculated how much dark energy was needed to account for the observed acceleration. They found that they needed a lot—about 60 percent of the critical density. Which is also precisely how much extra mass and energy cosmologists needed to make a flat universe. "We were stunned," recalls Perlmutter, "and we have spent the past few years trying to figure out how it could be wrong." Not only have they failed to find any errors, new data from other tests completed within the past year are confirming their results.

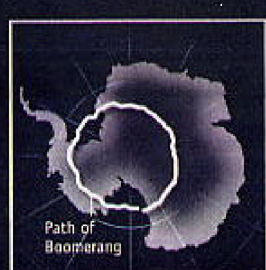
Like a cymbal crash, the echo of the Big Bang is not a single pure tone. Instead, the vibrations that are imprinted on the cosmic microwave background are composed of a primary tone followed by weaker overtones at successively smaller wavelengths. The wavelengths of each tone depend on the size of the universe at the moment light broke free of matter, which in turn depends upon the universe's geometry. If the universe is flat, then the wavelength of the primary tone, and the size of the most common bump in the cosmic microwave background, should be about 1 degree across when seen from Earth. The Cosmic Background Explorer mission, however, did not have the sharp eyesight necessary to spot blobs that small. "It was just a blurry image of lumps and bumps," says Caltech cosmologist Andrew Lange.

That is not a problem for a new generation of cosmic microwave background telescopes. Sporting state-of-the-art detectors, ground-based telescopes like the Microwave

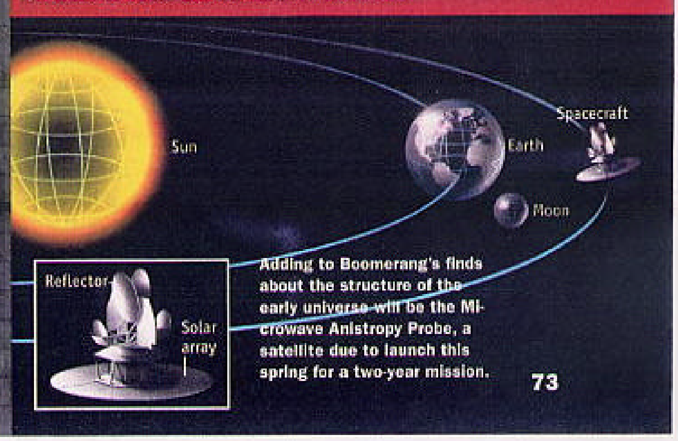
ANTARCTIC HEAT HUNTER



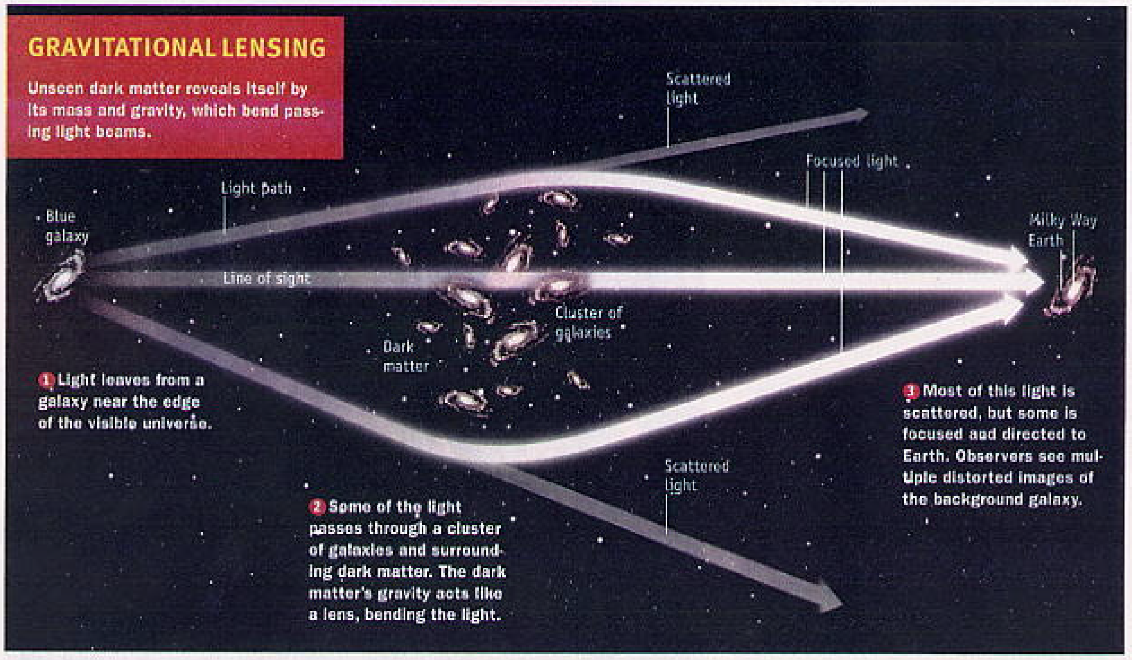
A 28-million-cubic-foot balloon circled Antarctica in 10 and a half days in late 1998, hoisting a telescope above 99 percent of Earth's atmosphere. Called the Balloon Observatory of Millimetric Extragalactic Radiation and Geophysics, or Boomerang, it searched for tiny variations in radiant heat that are left over from the Big Bang.



PROBING TEMPERATURE DIFFERENCES



Adding to Boomerang's finds about the structure of the early universe will be the Microwave Anistropy Probe, a satellite due to launch this spring for a two-year mission.



Anisotropy Telescope in the Chilean Andes and high-altitude balloons such as the Balloon Observations Of Millimetric Extragalactic Radiation and Geophysics (Boomerang) and the Millimeter Anisotropy eXperiment IMaging Array (Maximi) can find every blob down to less than one-sixth of a degree, or 10 arc minutes, across. "That is less than one-third the size of a full moon," says Lange, the principal investigator for Boomerang.

Recent results from the three telescopes all agree: The wavelength of the primary tone is one degree; the universe is flat. "They are amazingly, strikingly consistent," says University of California-Berkeley cosmologist Paul Richards, the principal investigator for Maxima. "So it is likely we got the right answer."

But if the universe is flat, what is dark energy? Although there are a number of proposals, says Perlmutter, no one really has any clue what it could be. And the best theoretical calculation of the value of the cosmological constant overestimates the weight of all the dark energy in the universe by a whopping factor of 10^{100}! Exercising his gift for understatement, Turner wonders if "maybe we are missing some deep principle."

Part of the problem is that astronomers don't know where all the dark matter is hidden. Dark matter in galaxies and clusters of galaxies can be found by observing its gravitational pull on orbiting stars. But what lurks in the immense voids between the galaxies? "We are looking at the whitecaps on the surface," says Tony Tyson, a cosmologist at Lucent Technologies' Bell Labs in Murray Hill, New Jersey, "but we need to find the mass of the ocean. It is the Holy Grail of cosmology." So Tyson and his collaborators have worked out a method for weighing the oceans of dark matter that seem to flood the universe.

They call it weak gravitational lensing. Any concentration of mass warps the surrounding fabric of space-time. Light passing by the mass follows a curved path similar to the track of a marble rolling in a bowl. So if the light from a faraway galaxy encounters dark matter on its journey to Earth, the galaxy's shape will be distorted, or lensed, in the same way heat ripples make the distant highway shimmer. "It is a cosmic mirage," says Tyson. By combining images of millions of galaxies, Tyson's team hopes to create a 3-D movie of the evolution of all the mass in the universe. "It should be really beautiful stuff," says Tyson. Tegmark agrees. "These are the first shots in another revolution in cosmology," he says.

And you ain't seen nothing yet. Perlmutter's search continues to turn up new supernovae (82 at the time of writing) and other groups have jumped in, steadily refining the picture of the accelerating universe. The Boomerang and Maxima balloons will return to the stratosphere in the next two years to snap more pictures of the cosmic microwave background. These experiments will be accompanied by the Microwave Anisotropy Probe, a satellite scheduled for launch in 2001. On the drafting table are both a Dark Matter Telescope dedicated to the search for weak lensing and the SuperNova Acceleration Project, a satellite for measuring cosmic acceleration.

With such a formidable array of hardware at scientists' disposal, it is not hard to imagine that they will soon solve the puzzle of dark energy. "A whole range of areas are really blooming," says Tegmark, "so even if one fails dismally, there is still no way we can fail." If they succeed, the venerable Standard Hot Big Bang will have to be swallowed up by something new and unforeseen. No current theory, not even inflation, predicts the presence of dark energy. So is Turner sad to see the once mighty standard model yielding so quickly to the onslaught of new information? Not in the least. "This is the way science works," he says cheerfully. "Cosmology is entering a golden age."